Aircraft Rotor Surface Coating Qualification Testing

Contract Number #W31P4Q-05-D-R003
Project Number #NP05007610

Aircraft Rotor Surface Coating
Technical Report Summary
Final Report
Revision 1 - October 25, 2006

Submitted by

National Center for Defense Manufacturing & Machining
1600 Technology Way
Latrobe, PA 15650
(724) 539-4772 phone
(724) 539-5094 fax
www.ncdmm.org

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
25 OCT 2006	**Final, Technical**	**25-10-2005 to 24-09-2006**

4. TITLE AND SUBTITLE
Aircraft Rotor Surface Coating Qualification Testing Aircraft Rotor Surface Coating

5a. CONTRACT NUMBER: **W31P4Q-05-D-R003**
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER: **NP05007610**
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Center for Defense Manufacturing & Machining,1600 Technology Way,Latrobe,PA,15650

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Due to the harsh environment and operating conditions of military aircraft rotor blades, the maintenance costs are extensive. Currently the Department of Defense (DoD) is interested in pursuing a new coating that could be applied to various helicopter rotor blades that would increase the life over the current method. The Aviation and Missile Research, Development and Engineering Center (AMRDEC) located at Redstone Arsenal, AL selected the NCDMM to coordinate the initial effort to qualify a new aircraft rotor blade coating for AMRDEC’s further consideration. The benefit to the DoD would be reduced maintenance costs and potentially safer aircraft operations. This test is only an initial qualification and further qualification and testing will be required before any field applications are tested. The objective of this initiative was to perform particle and rain erosion tests on coated samples from several coating suppliers along side control specimens coated with the current Poly Tape method for DoD aircraft rotor blades. The results from the coated test samples will be compared to those from the control specimens.

15. SUBJECT TERMS
AMRDEC; NCDMM; Aircraft Rotor Surface Coating

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**1**	**29**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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National Center for Defense Manufacturing and Machining

1.0 Executive Summary

The National Center for Defense Manufacturing & Machining (NCDMM), a government sponsored Manufacturing Technology Center, was established in 2003 to address and support the broad manufacturing and machining needs of the U.S. Department of Defense (DoD) and it suppliers.

The mission of the NCDMM is to develop and deliver state-of-the-art manufacturing processes and solutions to ensure the quality, affordability, maintainability, and rapid deployment of existing and yet to be developed defense systems.

The impact of the NCDMM efforts has been demonstrated through the execution of structured projects that utilize proper manufacturing and machining technologies and practices as well as training facility staff through a managed migration of those technologies and practices, resulting in an average reduction in operation and support costs of more than 30 percent. The projects conducted by the NCDMM have lowered costs, improved quality and extended service life of the component system and the process by which that component system is supported as well as improved the skills of the workforce by the increased use of appropriate technologies and practices – moving from current, often out-dated, practices to state-of-the-market and state-of-the-art methods.

The NCDMM will continue to serve as a national resource to identify critical opportunities within the DoD Industrial Base and capitalize on those opportunities by providing and implementing solutions resulting in reduction of costs while improving product quality through cost-effective manufacturing and machining processes.

The erosion of leading edge airfoils due to environmental factors and the search for longer lasting and economically suitable solutions continues to be a pressing need. The intent of this project is to conduct an initial evaluation of different aircraft rotor blade coatings that could potentially withstand the standard particle and rain erosion tests and to compare those coating to the current Poly Tape coating used on aircraft rotor blades today.

This project was selected during the NCDMM's Project Call for Government Fiscal Year 2005. Saint-Gobain Advanced Ceramics located in Latrobe, PA and Conforma Clad® Incorporated located in New Albany, IN both submitted separate projects relating to rotor blade coating. With this, the NCDMM along with the Aviation and Missile Research, Development and Engineering Center (AMRDEC) decided to open the project to other coating suppliers to evaluate multiple coatings. From that initiative, MDS-PRAD Technologies Corp. located in Washington, DC and BWXT Y-12, L.L.C. located in Oak Ridge, TN also submitted coatings to be tested.

2.0 Introduction

2.1 Description of Purpose

Due to the harsh environment and operating conditions of military aircraft rotor blades, the maintenance costs are extensive. Currently the Department of Defense (DoD) is interested in pursuing a new coating that could be applied to various helicopter rotor blades that would increase the life over the current method.

The Aviation and Missile Research, Development and Engineering Center (AMRDEC) located at Redstone Arsenal, AL selected the NCDMM to coordinate the initial effort to qualify a new aircraft rotor blade coating for AMRDEC's further consideration.

The benefit to the DoD would be reduced maintenance costs and potentially safer aircraft operations. This test is *only* an initial qualification and further qualification and testing will be required before any field applications are tested.

2.2 Project Objective

The objective of this initiative was to perform particle and rain erosion tests on coated samples from several coating suppliers along side control specimens coated with the current Poly Tape method for DoD aircraft rotor blades. The results from the coated test samples will be compared to those from the control specimens.

Please Note: The rain erosion test was not performed on all specimens due to the cost of conducting the rain erosion test and the limited accessibility of the rain erosion test apparatus. Therefore, if a supplier submitted more than one coating, the coating that performed the best during the particle erosion test was used for the rain erosion test.

2.0 Particle and Rain Erosion Test Apparatus Description

2.1 Particle Erosion Test Apparatus

The University of Dayton Research Institute (UDRI), Dayton, OH maintains and operates the US Air Force's Particle Erosion Test Facility in Kettering Laboratories on the U.D. campus. This facility is part of the Air Force Research Laboratories Materials Degradation Test Facility.

The Particle Erosion Test Apparatus was designed and built in the early 1980's for the Defense Nuclear Agency to simulate the effects of flight through a low concentration solid particle (dust) environment, see Figure #1. Specific simulation requirements included particle sizes ranging from 38 to 250 μm, particle mass fluxes as low as 1mg/cm^2/min, particle velocities over a broad range of subsonic Mach numbers, and continuously adjustable impact angles from normal to 20 degrees (70 degrees angle of incidence). The following is a description of how the Particle Erosion Apparatus tests specimens:

- Dust particles are accelerated in a small diameter (approximately 0.25”) high-speed gas jet and directed onto the test specimen.
- Compressed air provides the transport gas stream with regulators and pressure transducers to measure and control the pressure at the nozzle inlet. Dust particles are metered into the transport gas stream from a pressurized screw feeder system.
- Dust velocity is determined as a function of the nozzle inlet pressure and the particle size by prior calibration.
- For a complete description of the Particle Erosion Test Apparatus, please see the UDRI web site at http://www.udri.udayton.edu/.

Figure #1
Particle Erosion Test Chamber

2.2 Rain Erosion Test Apparatus

UDRI maintains and operates the US Air Force’s Particle Erosion Test Facility at Wright-Patterson Air Force Base, near Dayton. This facility is part of the Air Force Research Laboratories Materials Degradation Test Facility.

The Rain Erosion Test Apparatus, see Figure #2, has a 35-year history as the national and international standard for test the rain erosion resistance of various materials. It is capable of attaining constant velocities up to 650 miles per hour (MPH). The test specimens are exposed to a calibrated one inch per hour simulated rainfall. Raindrop impacts are distributed randomly over the exposed surfaces of the test specimen. The following is a description of how the Rain Erosion Apparatus tests specimens:

- The rotating arm apparatus is an eight foot diameter, double arm blade designed to produce high tip velocities with zero lift and low drag coefficient.
- Duplicate test specimens are mounted at the leading edge, tip sections of the double rotating arm.
- The specimens are rotated at variable velocities between 100 to 650 MPH.
- The simulated rainfall is produced by four curved manifold quadrants simultaneously from a water storage tank. Drop size and drop rate are approximately 1.8 to 2.0mm and 6 to 7 drops per second, respectively.

- For a complete description of the Rain Erosion Test Apparatus, please see the UDRI web site at http://www.udri.udayton.edu/.

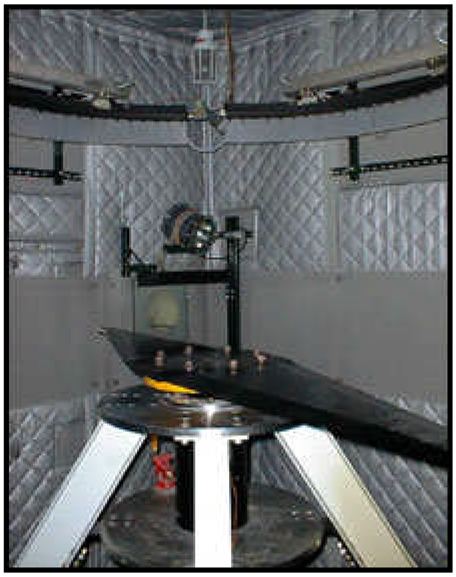


Figure #2
Rain Erosion Test Chamber

3.0 Particle and Rain Erosion Test Parameters

For this initiative, the following are the test parameters used for the particle and rain erosion tests.

3.1 Particle Erosion Test Parameters

- Velocity = 500 MPH
- Angle of Impact = 30°
- Particles = Dry Silica Dust
- Particle Size = 88 to 105µm
- Mass Loading = 10.00 g/cm^2 (maximum)
    - Intermediate measurements were taken at 3.0 g/cm^2 and 6.0 g/cm^2
    - Testing will be discontinued after major erosion

3.2 Rain Erosion Test Parameters

- Velocity = 500 MPH
- Angle of Impact = 90°
- Rain Rate = one inch per hour
- Raindrop Size = 1.8 to 2.0mm
- Raindrop Rate = 6 to 7 drops per second
- Duration = 120 minutes (maximum)

4.0 Particle and Rain Erosion Control Specimens

The following is the procedure used to prepare the 6061-T6 aluminum control specimens for the particle and rain erosion testing.

4.1 Control Specimen Preparation

- Serialize each control specimen on the surface that is not to be coated.
- Measure and record the thickness of the uncoated specimen.

4.2 Surface Preparation

- Wipe the surface of the specimen to be coated with cloth A-A-59323 moistened with methyl propye ketone.
- Lightly sand with a 360-grit aluminum abrasive cloth.
- Re-wipe the surface.

4.3 Application of Conversion Coating

- Apply the chemical conversion material, Alodine 1200S, using a spray or a brush.
- Allow the control specimen to dry at 60 to 100°F for 24 hours.
- Check the appearance of the conversion coating. It shall be continuous and free from areas of powdery or loose coating, voids, and any other defect or damages.

4.4 Application of Epoxy Primer

- Pour the required amount of Component 1 (base) into the clean container.
- Add equal amounts of Component 2 (converter) to the container.
- Stir slowly for 10 minutes.
- Thin the mixture for spraying by adding water per manufacturers instructions.
- Strain the mixture and let stand for 1 hour.
- Spray light, even coats of epoxy primer MIL-PRF-85582 on the prepared surface and allow drying for one hour at room temperature.
- Measure and record the primer thickness. It should be approximately 0.0010” to 0.0015”.

4.5 Application of Polyurethane Coating

- Spray two even coats of Polyurethane Lusterless Black No. 37038, MIL-C-46168, Type IV, National Stock No. 8010-01-146-2646, if available. If not available, replace with Aliphatic Polyurethane Coating Aircraft Black No. 37038, MIL-DTL-53039B.
- Allow drying for one hour at room temperature after each coat.
- Measure and record primer thickness. It should be approximately 0.0020” to 0.0025”.

4.6 Application of Poly Tape 8663

- Scuff the coated surface using 120-grit sandpaper.
- Clean the specimen using a cheesecloth dampened with denatured or isopropyl alcohol.
- Wipe dry with clean, dry cheesecloth. *Care must be taken not to touch or contaminate this surface from this point forward.*

- Cut the Poly Tape 8663 to fit the test specimen.
- Apply a thin coat of Adhesive Promoter #86 in the area to be covered by the tape, using a brush. The control specimens' minimum drying time is five minutes. The poly tape must be applied prior to one hour after the promoter application.
- Apply the Poly Tape 8663 by peeling off the backing. Bubbles greater than $0.2in^2$ are not allowed.
- Apply a second coat of Poly Tape 8663 by repeating the previous three steps.
- Allow the control specimen to dry for a minimum of 24 hours at room temperature.
- Measure and record the final thickness of the coated specimen. (See Figure #3 and #4 for an example of the control specimen.)

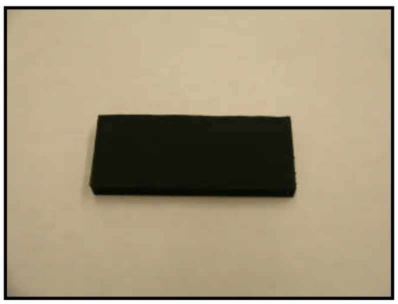


Figure #3
Control Specimen

Figure #4
Control Specimen

5.0 Particle and Rain Erosion Test Specimens

6061-T6 Aluminum substrate test specimens were provided by the NCDMM to interested parties for the application of their proposed erosion coating material (specimen size is described below in Figure #5 and Table #1). If agreed upon by the NCDMM, the interested parties could provide other substrate materials.

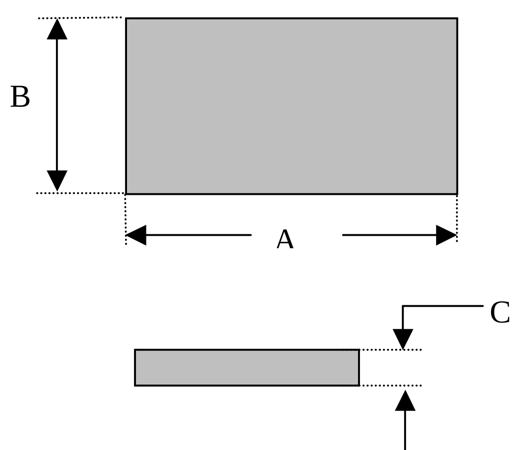


Figure #5
Standard Test Specimen

Table #1		
Standard Specimen Dimmensions		
A	B	C
2.435"	1.000"	0.250"
Tolerances		
+0.000" / -0.010"		

Once the coated test specimens were coated, they were then delivered from the interested parties to the NCDMM, where they were catalogued and shipped to UDRI for testing.

6.0 Control Specimen Test Results

The control specimens for the particle and rain erosion tests were prepared at UDRI. These tests were conducted to quantify the current rotor blade coating and to also be a base for comparison to the other coatings tested.

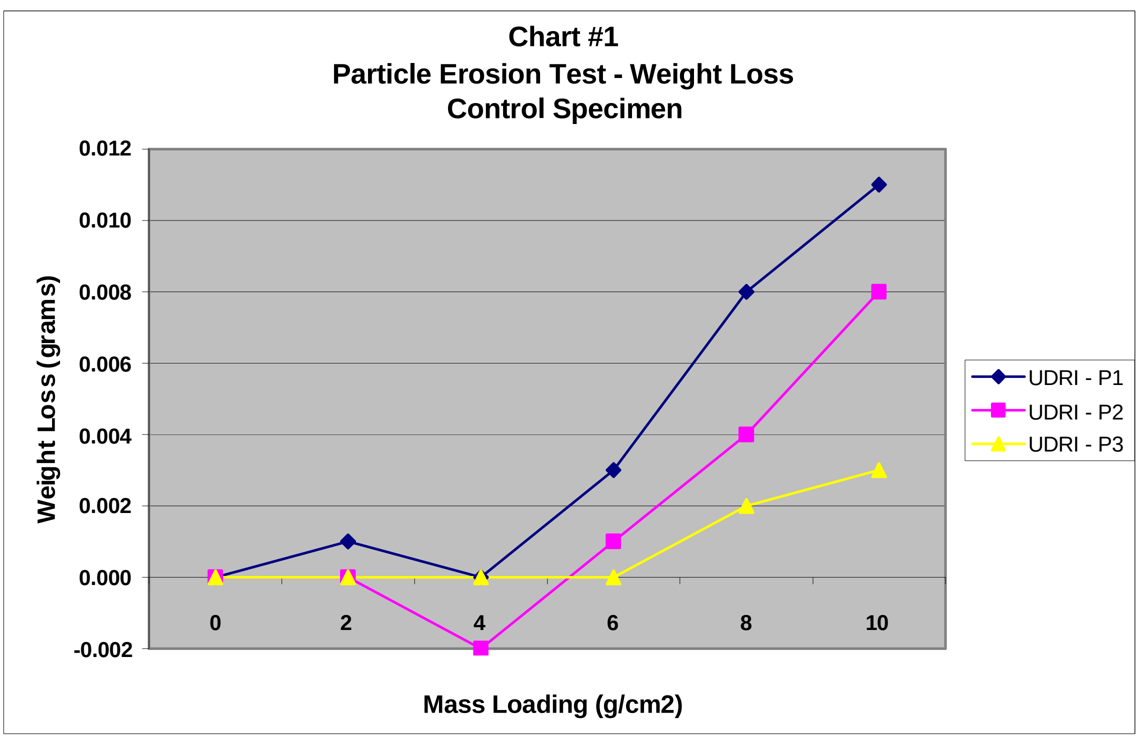
6.1 Particle Erosion Test – *Control Specimens*

The control specimens were first tested in the particle erosion chamber. The weight of each control specimen was measured and recorded after each mass loading cycle; see Table #2 below. Care was taken to make sure all the dry silica dust was removed from the control specimen prior to weighing.

Table #2
Particle Erosion Test
Control Specimens

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	*Mass Loading* 2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
UDRI–P1	Control Specimen	500	30	88 - 105	28.809	28.808	28.809	28.806	28.801	28.798
UDRI–P2	Control Specimen	500	30	88 - 105	28.754	28.754	28.756	28.753	28.750	28.746
UDRI–P3	Control Specimen	500	30	88 - 105	28.744	28.744	28.744	28.744	28.742	28.741

Chart #1 below shows a graphical representation of the weight loss for each control specimen tested after each mass loading cycle.



The control specimens performed very well in the particle erosion test. There was a maximum of 0.011 grams of weight loss from the UDRI–P1 control specimen. Visually, there were slight texture changes in the tape, however, the samples showed little signs of wear. The tape was not pitted, nor was it torn or separated from the base material; see Figures #5 and #6.

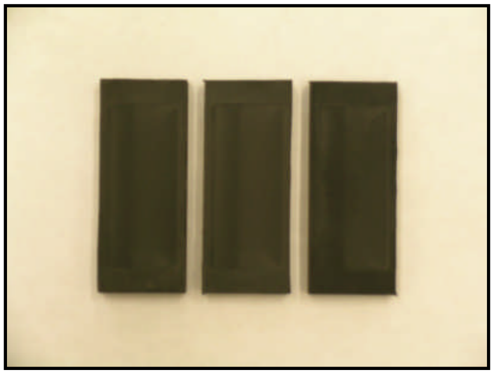


Figure #5
Control Specimens
UDRI-P1, P2, P3
Particle Erosion Test

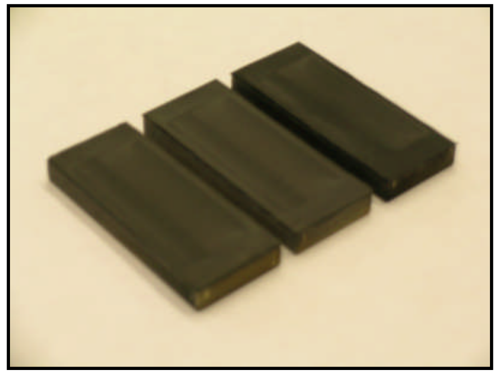


Figure #6
Control Specimens
UDRI-P1, P2, P3
Particle Erosion Test

6.2 Rain Erosion Test – *Control Specimens*

New control specimens were then tested in the rain erosion chamber. The time to failure was recorded for each control specimen; see Table #3 below. Two of the control specimens failed around 45 minutes into the test, while one specimen did last for the maximum test duration of 120 minutes.

Table #3
Rain Erosion Test
Control Specimens

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Rain Drop Size (mm)	Rain Drop Rate (drops/sec)	Rain Rate (inch/hour)	Test Duration (mins)	Time to Failure (mins)
UDRI-R1	Control Specimen	500	90	1.8 - 2.0	6 - 7	1.0	120.0	46.3
UDRI-R2	Control Specimen	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
UDRI-R3	Control Specimen	500	90	1.8 - 2.0	6 - 7	1.0	120.0	42.7

The control specimens did not perform well in the rain erosion test. Control specimens UDRI–R1 and UDRI–R3 had complete adhesion failure between the bottom tape layer and the primer. Control specimen UDRI–R2 did not have complete adhesion failure, however, at the end of the test, it was noticed that about 1/16” of creep (separation) occurred between the bottom tape layer and the primer; see Figures #7 and #8.

Figure #7
Control Specimens
UDRI-R1, R2, R3
Rain Erosion Test

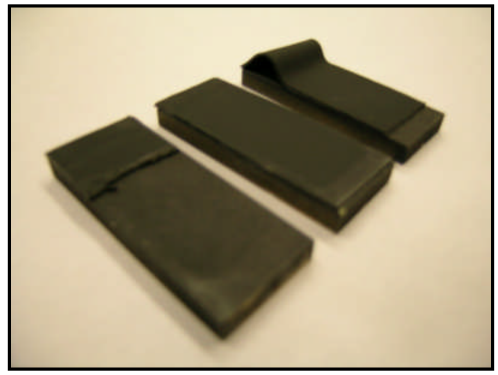


Figure #8
Control Specimens
UDRI-R1, R2, R3
Rain Erosion Test

7.0 Saint-Gobain Advanced Ceramics Test Results

Saint-Gobain Advanced Ceramics, Latrobe, PA supplied two different types of coatings for testing. They were as follows:

- **Rokide-C Chrome Oxide**
  - Base Material – 6061-T6 Aluminum
  - Base Coating – 80/20 NiChrome Boandcoat
  - Coating Process – Spray
  - Coating Thickness – Roughly 0.0023”
- **Ti-Elite Alumina/Titania**
  - Base Material – 6061-T6 Aluminum
  - Base Coating – 80/20 NiChrome Boandcoat
  - Coating Process – Spray
  - Coating Thickness – Roughly 0.0023”

7.1 Particle Erosion Test – *Saint-Gobain Rokide-C Chrome Oxide Coating*

The Rokide-C Chrome Oxide test specimens from Saint-Gobain were first tested in the particle erosion chamber. Test specimens STG-A-P1 and STG-A-P3 did not fit within the test fixture. Action was taken to grind the sides of the specimens. However, in doing so, some of the coating chipped off the base material. Therefore, only test specimen STG-A-P2 was tested and the weight was measured and recorded after each mass loading cycle; see Table #4 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #4 Particle Erosion Test *Saint-Gobain Coating Solutions* – Rokide-C Chrome Oxide										
Specimen Number	**Description**	**Velocity (MPH)**	**Angle of Impact (deg)**	**Particle Size (um)**	**Starting Weight (g)**	***Mass Loading***				
						2 g/cm2 Weight (g)	**4 g/cm2 Weight (g)**	**6 g/cm2 Weight (g)**	**8 g/cm2 Weight (g)**	**10 g/cm2 Weight (g)**
STG-A-P1	6061-T6 Aluminum Rokide-C Chrome Oxide	500	30	88 - 105	Did Not Test	~	~	~	~	~
STG-A-P2	6061-T6 Aluminum Rokide-C Chrome Oxide	500	30	88 - 105	29.130	29.108	29.083	29.054	29.030	29.007
STG-A-P3	6061-T6 Aluminum Rokide-C Chrome Oxide	500	30	88 - 105	Did Not Test	~	~	~	~	~

Figures #9 and #10 show the two test specimens that were chipped along with the middle specimen that was tested. There was some wear in the coating of the tested specimen, however, it did not break through to the base material, nor was there any visible pitting in the coating surface. This warranted possible further testing in the rain erosion chamber.

Figure #9
Saint-Gobain Coating Solutions
Rokide-C Chrome Oxide
STG-A-P1, P2, P3
Particle Erosion Test

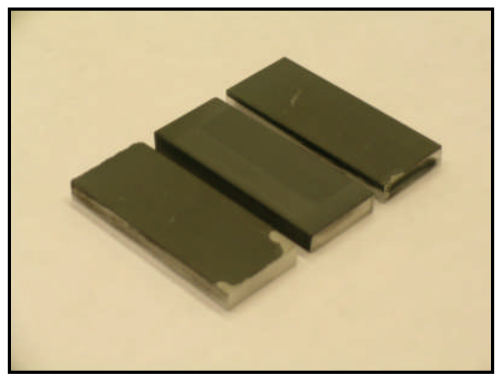


Figure #10
Saint-Gobain Coating Solutions
Rokide-C Chrome Oxide
STG-A-P1, P2, P3
Particle Erosion Test

7.2 Particle Erosion Test – *Saint-Gobain Ti-Elite Alumina/Titania Coating*

The Ti-Elite Alumina/Titania test specimens from Saint-Gobain were then tested in the particle erosion chamber. The weight of each test specimen was measured and recorded after each mass loading cycle; see Table #5 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #5 Particle Erosion Test *Saint-Gobain Coating Solutions* – TI-Elite Alumina/Titania										
Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	*Mass Loading*				
						2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
STG-B-P1	6061 T6 Alum. Substrate Ti-Elite Alumina/Titania	500	30	88 - 105	29.240	29.194	29.151	29.111	29.066	29.023
STG-B-P2	6061 T6 Alum. Substrate Ti-Elite Alumina/Titania	500	30	88 - 105	29.150	29.103	29.050	29.003	28.954	~
STG-B-P3	6061 T6 Alum. Substrate Ti-Elite Alumina/Titania	500	30	88 - 105	29.199	29.178	29.155	29.134	~	~
STG-B-P4	6061 T6 Alum. Substrate Ti-Elite Alumina/Titania	500	30	88 - 105	29.167	29.119	29.073	~	~	~
STG-B-P5	6061 T6 Alum. Substrate Ti-Elite Alumina/Titania	500	30	88 - 105	29.261	29.243	~	~	~	~

Figures #11 and #12 below show the Ti-Elite Alumina/Titania test specimens. There was uniform wear visible in the coating of each specimen. Some pitting was noticed even after the lowest mass loading of 2 g/cm2 was applied. However, the particles did not break through the coating to the base material. Due to the limitation on the number of tests that can be run on the rain erosion apparatus, only one type of coating could be tested. Therefore, since the Rokide-C Chrome Oxide coating did not show signs of pitting, it was selected for further testing in the rain erosion chamber.

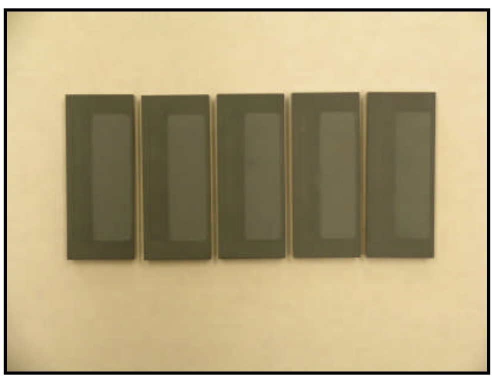


Figure #11
Saint-Gobain Coating Solutions
TI-Elite Alumina/Titania
STG-B-P1, P2, P3, P4, P5
Particle Erosion Test

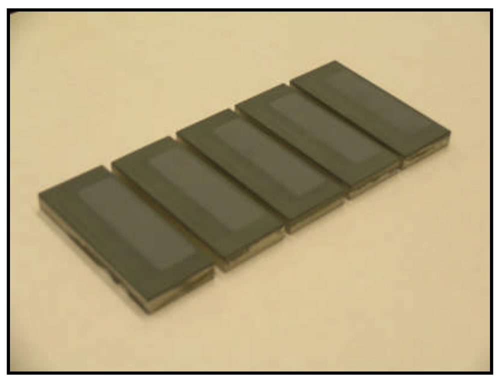
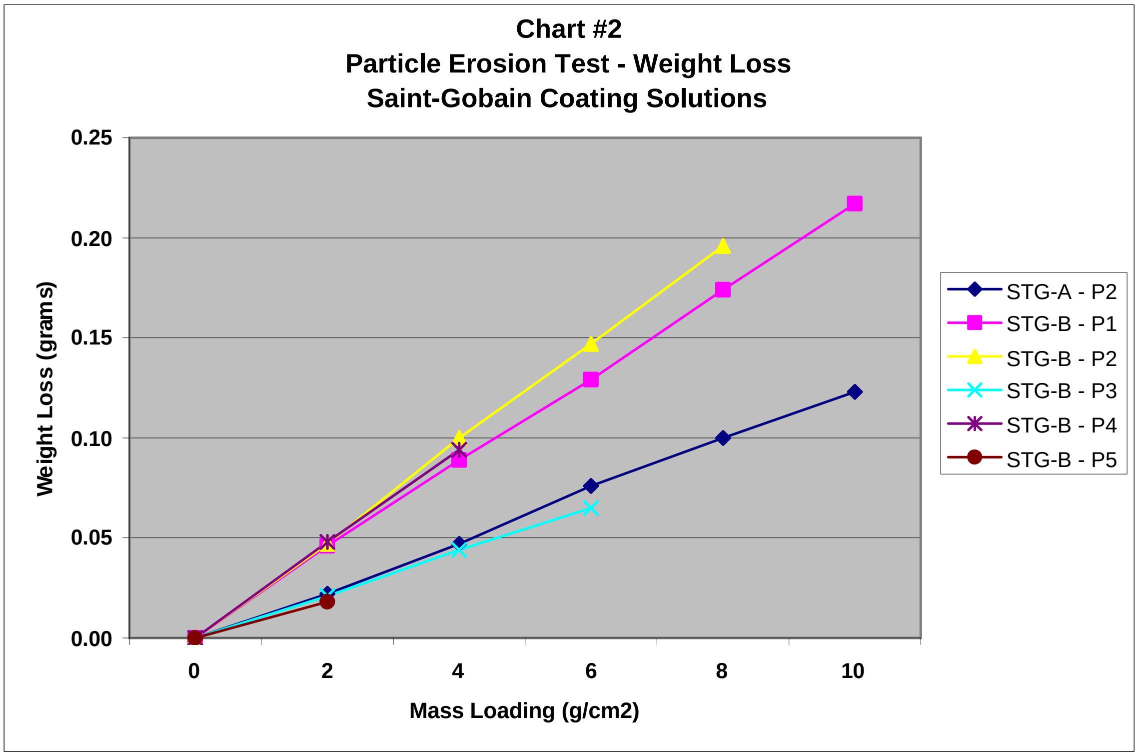


Figure #12
Saint-Gobain Coating Solutions
TI-Elite Alumina/Titania
STG-B-P1, P2, P3, P4, P5
Particle Erosion Test

Chart #2 shows a graphical representation of the weight loss for each test specimen tested after each mass loading cycle.



7.3 Rain Erosion Test – *Saint-Gobain Rokide-C Chrome Oxide Coating*

New Rokide-C Chrome Oxide test specimens were then tested in the rain erosion chamber. The time to failure was recorded for each control specimen; see Table #6 below.

Table #6
Rain Erosion Test
***Saint-Gobain Coating Solutions* – Rokide C Chrome Oxide**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Rain Drop Size (mm)	Rain Drop Rate (drops/sec)	Rain Rate (inch/hour)	Test Duration (mins)	Time to Failure (mins)
STG-A-R1	6061-T6 Aluminum Rokide-C Chrome Oxide	500	90	1.8 - 2.0	6 - 7	1.0	120.0	13.4
STG-A-R2	6061-T6 Aluminum Rokide-C Chrome Oxide	500	90	1.8 - 2.0	6 - 7	1.0	120.0	18.0
STG-A-R3	6061-T6 Aluminum Rokide-C Chrome Oxide	500	90	1.8 - 2.0	6 - 7	1.0	120.0	20.5

Each test specimen failed only minutes into the test. All the test specimens failed by cratering near the center of the test specimen and then exposing the base material; see Figures #13 and #14.

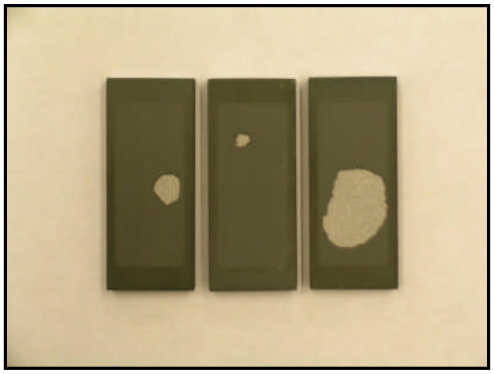


Figure #13
Saint-Gobain Coating Solutions
Rokide-C Chrome Oxide
STG-A-R1, R2, R3
Rain Erosion Test

Figure #14
Saint-Gobain Coating Solutions
Rokide-C Chrome Oxide
STG-A-R1, R2, R3
Rain Erosion Test

7.4 Erosion Test Conclusion – *Saint-Gobain Rokide-C Chrome Oxide Coating*

Compared to the control specimens, the Saint-Gobain Rokide-C Chrom Oxide coating performed comparable in the particle erosion test but failed to match the control specimens in the rain erosion test.

8.0 MDS-PRAD Technologies Corp. Test Results

MDS-PRAD Technologies Corporation, Washington, DC supplied the following coating for testing:

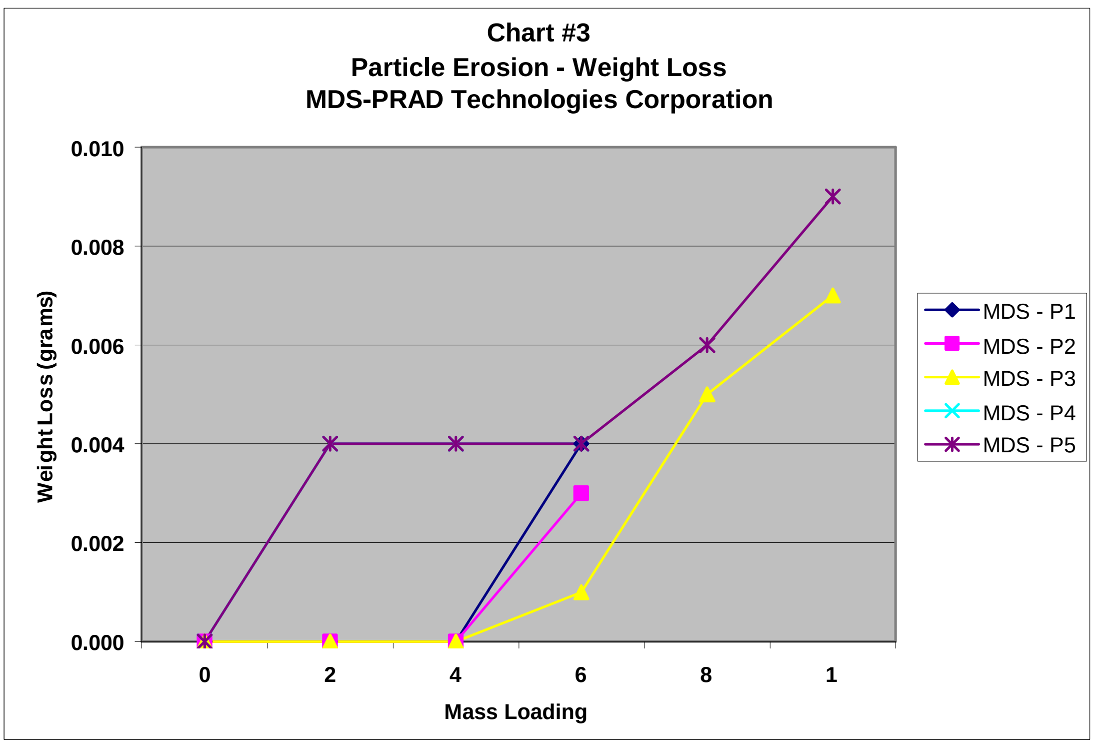
- **Titanium ER-7 TiN**
  - Base Material – Titanium ASTM B265
  - Base Coating – N/A
  - Coating Process – Cathodic Arc Physical Vapor Deposition
  - Coating Thickness – Less Than 35 Microns (specified by manufacturer)

8.1 Particle Erosion Test – *MDS-PRAD Titanium ER-7 TiN Coating*

The test specimens from MDS-PRAD were first tested in the particle erosion chamber. The weight of each test specimen was measured and recorded after each mass loading cycle; see Table #7 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #7 Particle Erosion Test ***MDS-PRAD Technologies Corp.* – Titanium ER-7 TiN**										
Specimen Number	**Description**	**Velocity (MPH)**	**Angle of Impact (deg)**	**Particle Size (um)**	**Starting Weight (g)**	***Mass Loading***				
						2 g/cm2 Weight (g)	**4 g/cm2 Weight (g)**	**6 g/cm2 Weight (g)**	**8 g/cm2 Weight (g)**	**10 g/cm2 Weight (g)**
MDS - P1	Titanium ASTM B265 Titanium ER-7 TiN	500	30	88 - 105	43.595	43.595	43.595	43.591	~	~
MDS - P2	Titanium ASTM B265 Titanium ER-7 TiN	500	30	88 - 105	43.578	43.578	43.578	43.575	~	~
MDS - P3	Titanium ASTM B265 Titanium ER-7 TiN	500	30	88 - 105	43.231	43.231	43.231	43.230	43.226	43.224
MDS - P4	Titanium ASTM B265 Titanium ER-7 TiN	500	30	88 - 105	44.793	44.789	47.789	44.789	~	~
MDS - P5	Titanium ASTM B265 Titanium ER-7 TiN	500	30	88 - 105	44.669	44.665	44.665	44.665	44.663	44.660

Chart #3 below shows a graphical representation of the weight loss for each test specimen after each mass loading cycle.



Figures #15 and #16 below show the Titanium ER-7 TiN test specimens after testing in the particle erosion chamber. The first three test specimens showed significant erosion and pitting into the Titanium base material. The last two specimens showed less wear and pitting.

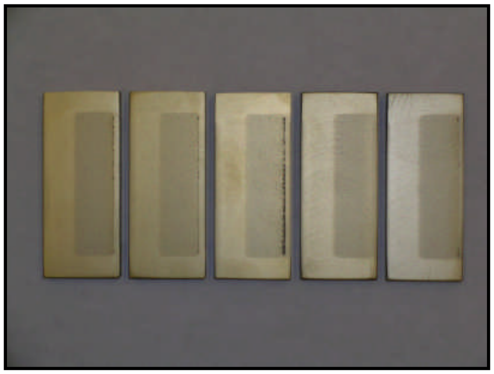


Figure #15
MDS-PRAD Technologies Corporation
Titanium ER-7 TiN
MDS-P1, P2, P3, P4, P5
Particle Erosion Test

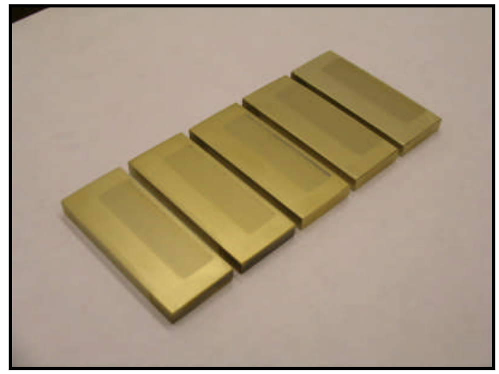


Figure #16
MDS-PRAD Technologies Corporation
Titanium ER-7 TiN
MDS-P1, P2, P3, P4, P5
Particle Erosion Test

8.2 Rain Erosion Test – *MDS-PRAD Titanium ER-7 TiN Coating*

New Titanium ER-7 TiN test specimens were then tested in the rain erosion chamber. Each test specimen lasted till the maximum test duration of 120 minutes; see Table #8 below.

Table #8
Rain Erosion Test
MDS-PRAD Technologies Corp. – Titanium ER-7 TiN

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Rain Drop Size (mm)	Rain Drop Rate (drops/sec)	Rain Rate (inch/hour)	Test Duration (mins)	Time to Failure (mins)
MDS-R1	Titanium ASTM B265 Titanium ER-7 TiN 22 µm	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
MDS-R2	Titanium ASTM B265 Titanium ER-7 TiN 22 µm	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
MDS-R3	Titanium ASTM B265 Titanium ER-7 TiN 22 µm	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0

After the rain erosion testing, the Titanium ER-7 TiN test specimens showed little signs of wear, however, there was scattered pitting evident and the base material becoming exposed in each sample after 60 minutes of rain erosion testing. After 120 minutes of testing, the pitting was more pronounced and erosion was occurring on the base material; see Figures #17 and #18.

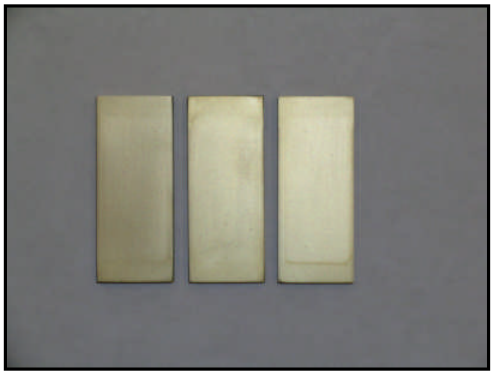


Figure #17
MDS-PRAD Technologies Corporation
Titanium ER-7 TiN
MDS-R1, R2, R3
Rain Erosion Test

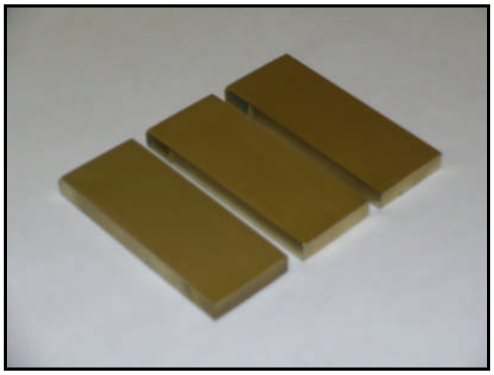


Figure #18
MDS-PRAD Technologies Corporation
Titanium ER-7 TiN
MDS-R1, R2, R3
Rain Erosion Test

8.3 Erosion Test Conclusion – *MDS-PRAD Titanium ER-7 TiN Coating*

Compared to the control specimens, the MDS-PRAD Titanium ER-7 TiN coating did not perform as well as the control specimens in the particle erosion test but did perform better than the control specimens in the rain erosion test, lasting the full 120 minutes. Further research should be warranted to this coating to see if it can be applied thicker to other base materials and if it can stand up to further testing.

9.0 Conforma Clad® Incorporated Test Results

Conforma Clad® Incorporated, New Albany, IN supplied four different types of coatings for testing. They were as follows:

- **WC200 - 62% Tungsten Carbide, 30% Nickel, 6% Chromium, 2% Other**
  - Base Material – 410 SS
  - Base Coating – Low Temperature Adhesive
  - Coating Process – Cloth
  - Coating Thickness – Roughly 0.090”
- **WC219 - 48% Tungsten Carbide, 39% Nickel, 8% Chromium, 5% Other**
  - Base Material – 410 SS
  - Base Coating – Low Temperature Adhesive
  - Coating Process – Cloth
  - Coating Thickness – Roughly 0.090”
- **WC210 - 55% Tungsten Carbide, 34% Nickel, 7% Chromium, 4% Other**
  - Base Material – 316 SS
  - Base Coating – Low Temperature Adhesive
  - Coating Process – Cloth
  - Coating Thickness – Roughly 0.090”

- **WC219 - 48% Tungsten Carbide, 39% Nickel, 8% Chromium, 5% Other**
    - Base Material – 316 SS
    - Base Coating – Low Temperature Adhesive
    - Coating Process – Cloth
    - Coating Thickness – Roughly 0.090”

9.1 Particle Erosion Test – *Conforma Clad® Carbide WC200 Coating / 410 SS*

The Carbide Coating WC200 test specimens on the 410 SS base material from Conforma Clad® were first tested in the paticle erosion chamber. The weight was measured and recorded after each mass loading cycle; see Table #9 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #9
Particle Erosion Test
***Conforma Clad® Incorporated* – Carbide Coating WC200**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	Mass Loading				
						2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
CCI-A-P1	410 SS Carbide Coating WC200	500	30	88 - 105	87.922	87.897	87.884	87.873	87.864	87.855
CCI-A-P2	410 SS Carbide Coating WC200	500	30	88 - 105	87.308	87.285	87.270	87.258	87.241	87.238
CCI-A-P3	410 SS Carbide Coating WC200	500	30	88 - 105	88.290	88.269	88.262	88.254	88.251	88.243

Figures #19 and #20 show the Carbide Coating WC200 test specimens on the 410 SS base material after the particle erosion test. The coating was worn however; the base material was not exposed on any of the test specimens. Pitting and voids appeared in the coating on all the test specimens. It is not clearly defined from the testing on whether or not the voids were pre-existing within the coating itself.

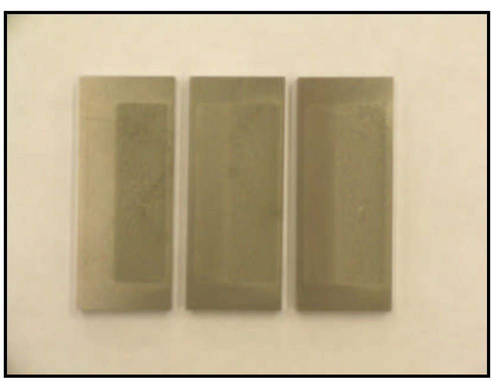


Figure #19
Conforma Clad® Incorporated
Carbide Coating WC200
CCI-A-P1, P2, P3
Particle Erosion Test

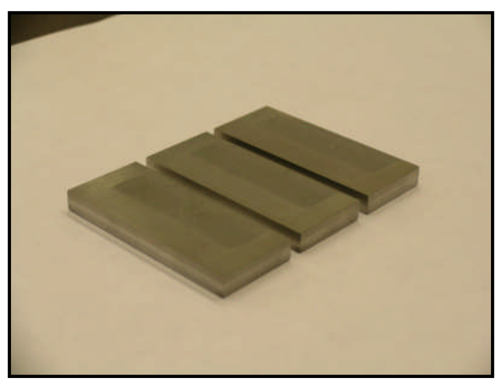


Figure #20
Conforma Clad® Incorporated
Carbide Coating WC200
CCI-A-P1, P2, P3
Particle Erosion Test

9.2 Particle Erosion Test – *Conforma Clad® Carbide WC219 Coating / 410 SS*

The Carbide Coating WC219 test specimens on the 410 SS base material from Conforma Clad® were the second to be tested in the particle erosion chamber. The weight of each test specimen was measured and recorded after each mass loading cycle; see Table #10 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #10
Particle Erosion Test
***Conforma Clad® Incorporated* – Carbide Coating WC219**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	*Mass Loading*				
						2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
CCI-B-P1	410 SS Carbide Coating WC219	500	30	88 - 105	88.162	88.135	88.118	88.101	88.086	88.070
CCI-B-P2	410 SS Carbide Coating WC219	500	30	88 - 105	88.387	88.355	88.339	88.318	88.303	88.285
CCI-B-P3	410 SS Carbide Coating WC219	500	30	88 - 105	87.789	87.755	87.736	87.720	87.679	87.679

Figures #21 and #22 show the Carbide Coating WC219 test specimens on the 410 SS base material after the particle erosion test. Again, the coating was worn however; the base material was not exposed on any of the test specimens. More pitting and voids appeared in the coating on all the test specimens. It is not clearly defined from the testing on whether or not the voids were pre-existing within the coating itself.

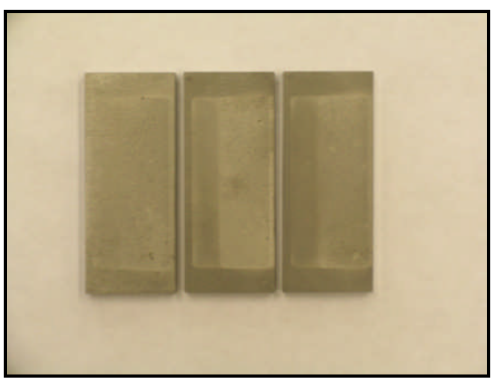


Figure #21
Conforma Clad® Incorporated
Carbide Coating WC219
CCI-B-P1, P2, P3
Particle Erosion Test

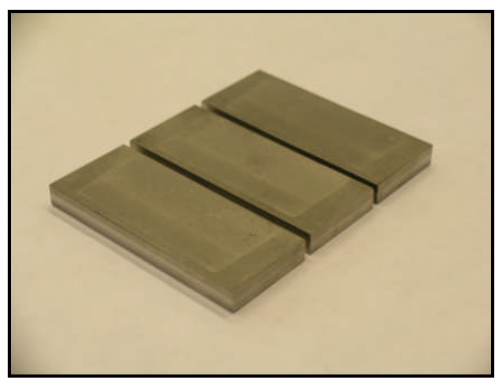


Figure #22
Conforma Clad® Incorporated
Carbide Coating WC219
CCI-P1, P2, P3
Particle Erosion Test

9.3 Particle Erosion Test – *Conforma Clad® Carbide WC210 Coating / 316 SS*

The Carbide Coating WC210 test specimens on the 316 SS base material from Conforma Clad® were the third to be tested in the particle erosion chamber. The weight of each test specimen was measured and recorded after each mass loading cycle; see Table #11 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #11
Particle Erosion Test
***Conforma Clad® Incorporated* – Carbide Coating WC210**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	*Mass Loading*				
						2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
CCI-C - P1	316 SS Carbide Coating WC210	500	30	88 - 105	87.008	86.988	86.974	86.961	86.949	86.941
CCI-C - P2	316 SS Carbide Coating WC210	500	30	88 - 105	87.079	87.053	87.039	87.027	~	~
CCI-C - P3	316 SS Carbide Coating WC210	500	30	88 - 105	89.140	~	~	89.089	89.073	89.06

Figures #23 and #24 show the Carbide Coating WC210 test specimens on the 316 SS base material after the particle erosion test. Again, the coating was worn however; the base material was not exposed on any of the test specimens. Pitting and voids appeared in the coating on all the test specimens. It is not clearly defined from the testing on whether or not the voids were pre-existing within the coating itself.

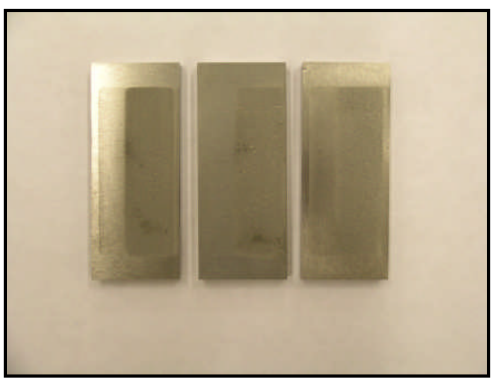


Figure #23
Conforma Clad® Incorporated
Carbide Coating WC210
CCI-C-P1, P2, P3
Particle Erosion Test

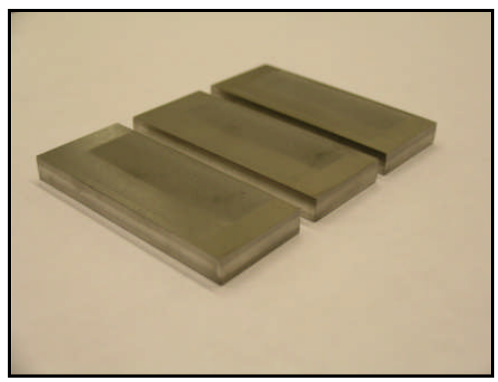


Figure #24
Conforma Clad® Incorporated
Carbide Coating WC210
CCI-C -P1, P2, P3
Particle Erosion Test

9.4 Particle Erosion Test – *Conforma Clad® Carbide WC219 Coating / 316 SS*

The Carbide Coating WC219 test specimens on the 316 SS base material from Conforma Clad® were the fourth to be tested in the particle erosion chamber. The weight of each test specimen was measured and recorded after each mass loading cycle; see Table #12 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #12
Particle Erosion Test
***Conforma Clad® Incorporated* – Carbide Coating WC219**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	*Mass Loading* 2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
CCI-D - P1	316 SS Carbide Coating WC219	500	30	88 - 105	88.284	88.259	88.240	88.224	88.209	88.195
CCI-D - P2	316 SS Carbide Coating WC219	500	30	88 - 105	88.755	88.727	88.709	88.695	88.680	88.664
CCI-D - P3	316 SS Carbide Coating WC219	500	30	88 - 105	88.354	88.324	88.300	88.285	88.262	88.245

Figures #25 and #26 show the Carbide Coating WC219 test specimens on the 316 SS base material after the particle erosion test. Again, similar to the first three coatings, the coating was worn however; the base material was not exposed on any of the test specimens. Pitting and voids appeared in the coating on all the test specimens. It is not clearly defined from the testing on whether or not the voids were pre-existing within the coating itself. Several cracks also appeared on the coating surface. It is not known if these cracks go through the coating, down to the base material.

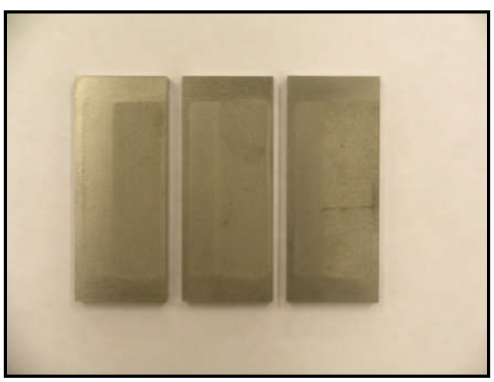


Figure #25
Conforma Clad® Incorporated
Carbide Coating WC210
CCI-D-P1, P2, P3
Particle Erosion Test

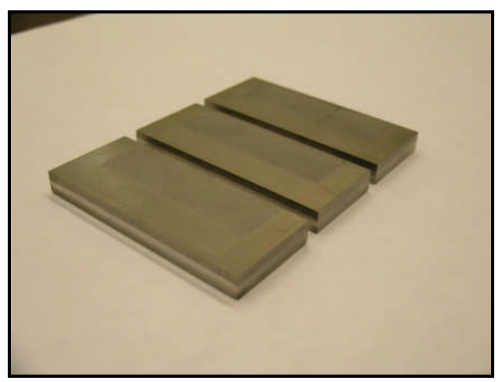
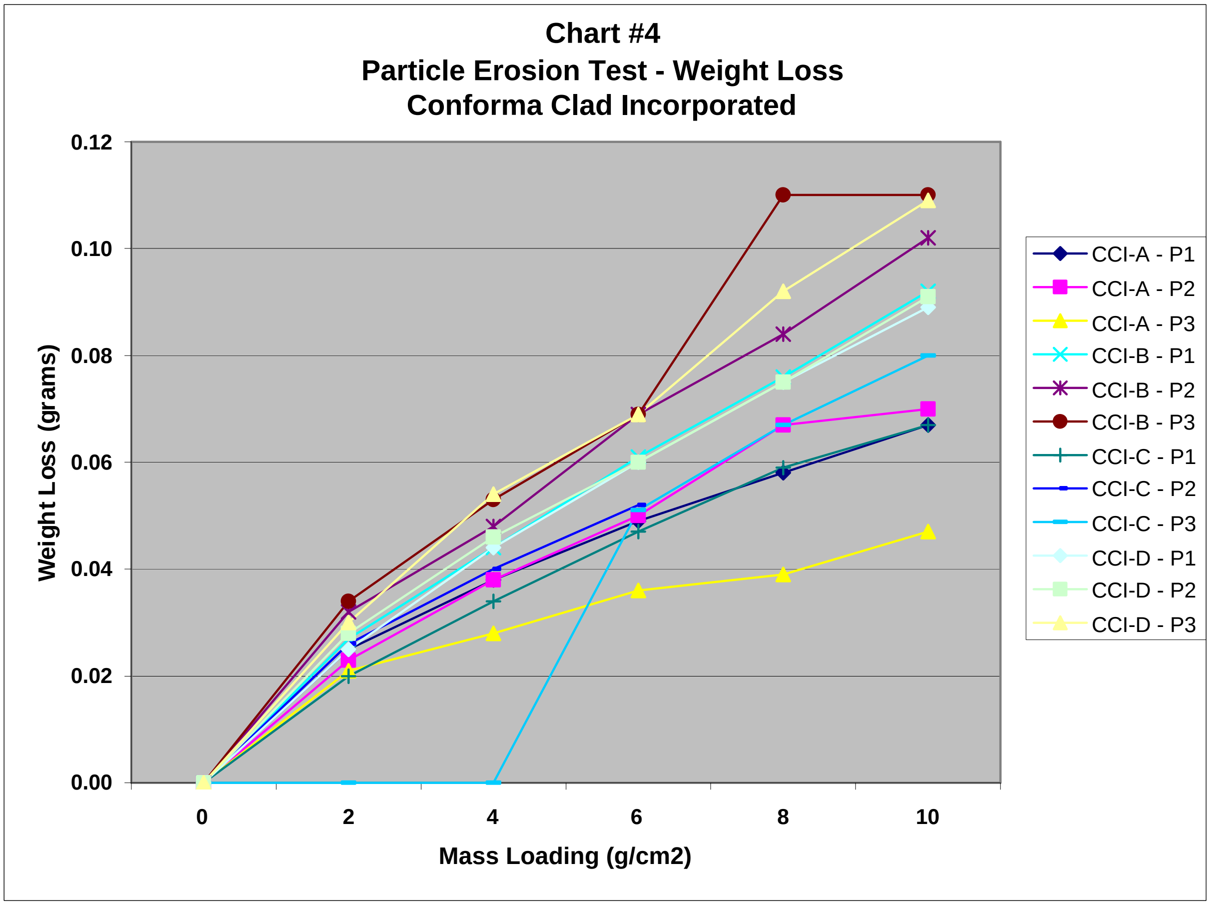


Figure #26
Conforma Clad® Incorporated
Carbide Coating WC210
CCI-D-P1, P2, P3
Particle Erosion Test

Chart #4 shows a graphical representation of the weight loss for each test specimen tested after each mass loading cycle.



Due to the limitation on the number of tests that can be run on the rain erosion apparatus, only one type of coating could be tested. All the coatings performed very similarly. Looking at the data from Chart #4 above, the Carbide Coating WC200 on the 410 SS base material had on average, less weight loss then the other test specimens during the particle erosion tests. Therefore, the Carbide Coating WC200 on the 410 SS base material was further tested.

9.5 Rain Erosion Test – *Conforma Clad® Carbide Coating WC200 / 410 SS*

New Carbide Coating WC200 test specimens on the 410 SS base material were then tested in the rain erosion chamber. The time to failure was recorded for each control specimen; see Table #13 below.

Table #13 Rain Erosion Test ***Conforma Clad® Incorporated*** **– Carbide Coating WC200**								
Specimen Number	**Description**	**Velocity (MPH)**	**Angle of Impact (deg)**	**Rain Drop Size (mm)**	**Rain Drop Rate (drops/sec)**	**Rain Rate (inch/hour)**	**Test Duration (mins)**	**Time to Failure (mins)**
CCI-A-R1	410 SS Carbide Coating WC200	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
CCI-A-R2	410 SS Carbide Coating WC200	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
CCI-A-R3	410 SS Carbide Coating WC200	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0

After the rain erosion testing, the test specimens showed little signs of wear after the 120-minute test. However, there was scattered pitting evident in the coating, but the base material was not exposed on any of the test specimens; see Figures #27 and #28.

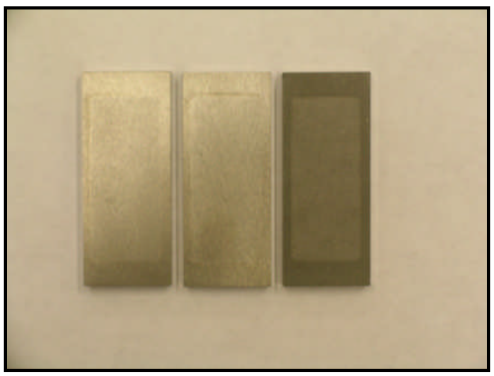


Figure #27
Conforma Clad® Incorporated
Carbide Coating WC200
CCI-A-R1, R2, R3
Rain Erosion Test

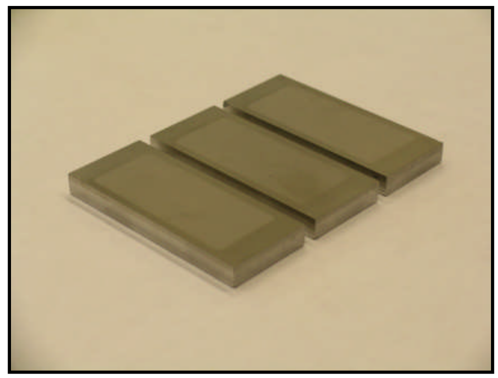


Figure #28
Conforma Clad® Incorporated
Carbide Coating WC200
CCI-A-R1, R2, R3
Rain Erosion Test

9.6 Erosion Test Conclusion – *Conforma Clad® Carbide Coating WC200 / 410 SS*

The Conforma Clad® Carbide Coating WC200 on the 410 SS base material not only out-performed the Control Specimens in the particle and rain erosion tests, but it also out-performed all the other test specimens in the particle and rain erosion tests. Further research should be warranted to this coating to see if it can be applied to other base materials and if it can stand up to further testing and reapplication.

10.0 BWXT Y-12, L.L.C. Test Results

BXWT Y-12, L.L.C., Oak Ridge, TN supplied the following coating for testing:

- **Metal Deposition**
  - Base Material – Titanium – Ti64
  - Base Coating – N/A
  - Coating Process – N/A
  - Coating Thickness – Varies

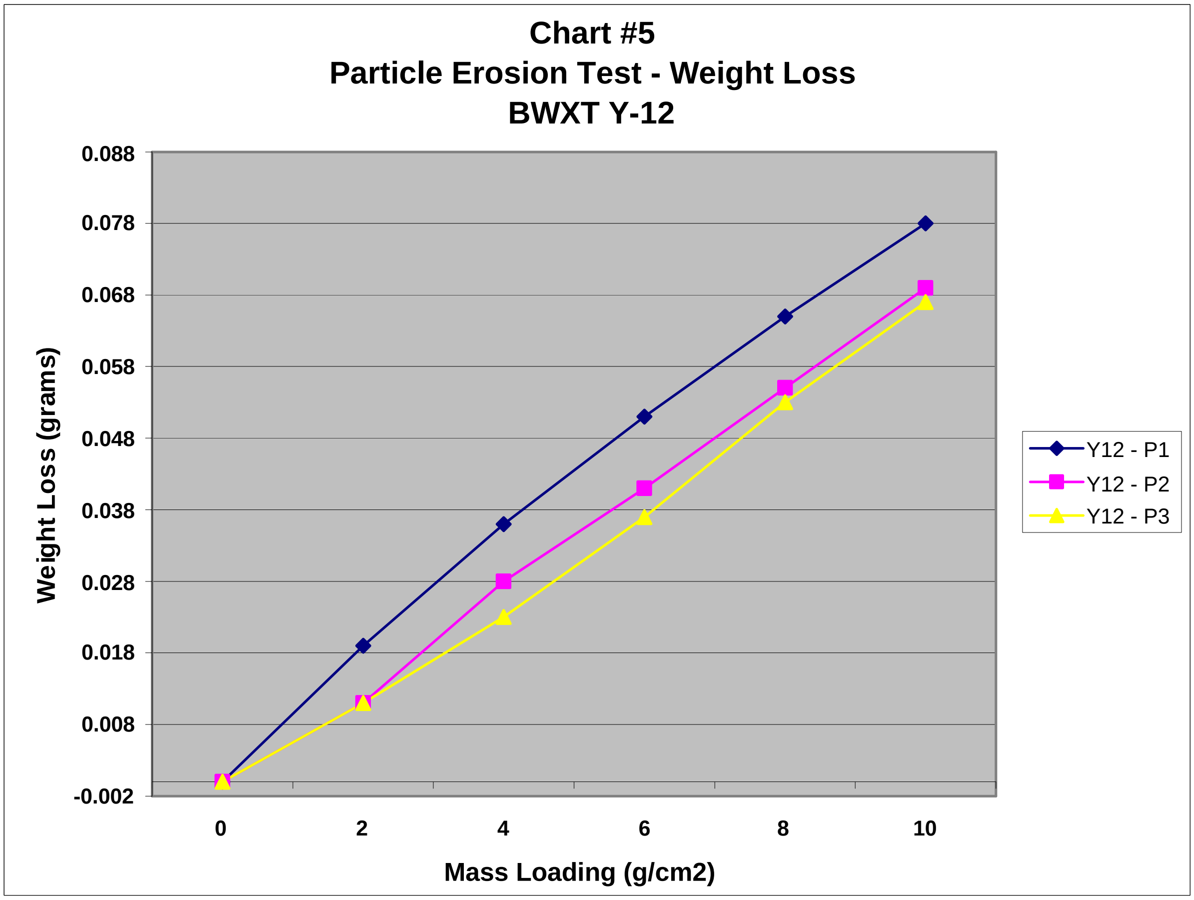
10.1 Particle Erosion Test – *BWXT Y-12 Metal Deposition*

The test specimens from BWXT Y-12 were first tested in the particle erosion chamber. The weight of each test specimen was measured and recorded after each mass loading cycle; see Table #14 below. Care was taken to make sure all the dry silica dust was removed from the test specimen prior to weighing.

Table #14
Particle Erosion Test
***BWXT Y-12* - Metal Deposition**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Particle Size (um)	Starting Weight (g)	*Mass Loading*				
						2 g/cm2 Weight (g)	4 g/cm2 Weight (g)	6 g/cm2 Weight (g)	8 g/cm2 Weight (g)	10 g/cm2 Weight (g)
Y12 - P1	Metal Deposition Titanium	500	30	88 - 105	52.056	52.037	52.020	52.005	51.991	51.978
Y12 - P2	Metal Deposition Titanium	500	30	88 - 105	52.557	52.546	52.529	52.516	52.502	52.488
Y12 - P3	Metal Deposition Titanium	500	30	88 - 105	53.565	53.554	53.542	53.528	53.512	53.498

Chart #5 below shows a graphical representation of the weight loss for each test specimen after each mass loading cycle.



Figures #29 and #30 below show the Metal Deposition test specimens after testing in the particle erosion chamber. The first specimen showed little sign of surface erosion, but severe surface deformation was evident. The other two specimens also showed little sign of surface erosion with some surface deformation; however, the surface deformation was not as pronounced as the first specimen.

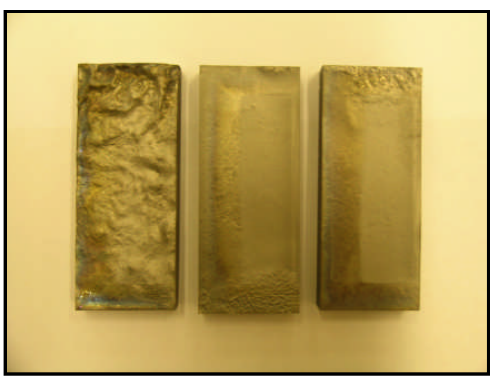


Figure #29
BWXT Y-12
Metal Deposition
Y12-P1, P2, P3
Particle Erosion Test

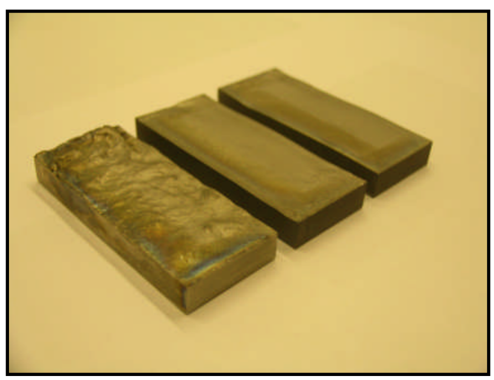


Figure #30
BWXT Y-12
Metal Deposition
Y12-P1, P2, P3
Particle Erosion Test

10.2 Rain Erosion Test – *BWXT Y-12 Metal Deposition*

New Metal Deposition test specimens were then tested in the rain erosion chamber. Each test specimen lasted till the maximum test duration of 120 minutes; see Table #15 below.

Table #15
Rain Erosion Test
***BWXT Y-12* – Metal Deposition**

Specimen Number	Description	Velocity (MPH)	Angle of Impact (deg)	Rain Drop Size (mm)	Rain Drop Rate (drops/sec)	Rain Rate (inch/hour)	Test Duration (mins)	Time to Failure (mins)
Y12 - R1	Metal Depostion Titanium	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
Y12 - R2	Metal Depostion Titanium	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0
Y12 - R3	Metal Depostion Titanium	500	90	1.8 - 2.0	6 - 7	1.0	120.0	120.0

After the rain erosion testing, all the Metal Deposition test specimens showed little signs of surface erosion; however, surface deformation was again very evident; see Figures #31 and #32.

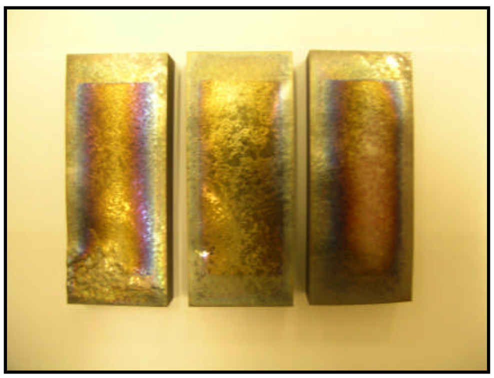


Figure #31
BWXT Y-12
Metal Deposition
Y12-R1, R2, R3
Rain Erosion Test

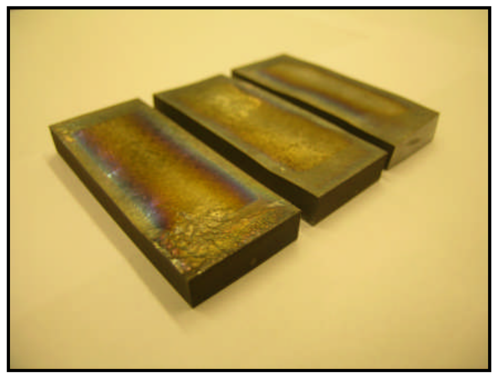


Figure #32
BWXT Y-12
Metal Deposition
Y12-R1, R2, R3
Rain Erosion Test

10.3 Erosion Test Conclusion – *BWXT Y-12 Metal Deposition*

Compared to the control specimens, the BWXT Y-12 Metal Deposition specimens did not perform well in the particle erosion test but performed slightly better in the rain erosion test. Even though surface erosion was not evident after either test, severe surface deformation was.

11.0 Blade Coating Test Results – Summary

The chart below is a quick reference illustrating the performance of each suppliers test specimen after the particle erosion and rain erosion tests. This chart also includes the performance of the control specimens.

Please Note: If a supplier submitted more than one coating, the coating that performed the best during the particle erosion test was used for the rain erosion test.

Chart #6
Quick Reference – Coating Results

Supplier	Coating	Base Material	Particle Erosion	Rain Erosion
Control Specimens	Poly Tape 8663	6061-T6 Aluminum	🟢	🔴
Saint-Gobain Advanced Ceramics	Rokide-C Chrome Oxide	6061-T6 Aluminum	🟢	🔴
Saint-Gobain Advanced Ceramics	Ti-Elite Alumina/Titania	6061-T6 Aluminum	🟡	*Not Tested*
MDS PRAD	Titanium ER-7 TiN	Titanium ASTM B265	🟡	🟡
Conforma Clad®	WC200	410 SS	🟢	🟡
Conforma Clad®	WC219	410 SS	🟡	*Not Tested*
Conforma Clad®	WC210	316 SS	🟡	*Not Tested*
Conforma Clad®	WC219	316 SS	🟡	*Not Tested*
BWXT Y-12	Metal Deposition	Titanium Ti64	🔴	🔴

Good Results 🟢

Fair Results 🟡

Poor Results 🔴

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United States Army
Army Material Command (AMC)
Research, Development and Engineering Command (RDECOM)
Aviation and Missile Research, Development and Engineering Center (AMRDEC)
Engineering Directorate (ED)
Manufacturing Science and Technology Division (MST)

Redstone Arsenal, Alabama

Scott A. Hofacker, PE – Program Manager 256.842.7992

scott.hofacker@us.army.mil

or Mike Cummings (Tiburon) 256.313.6496

mike.a.cummings@us.army.mil

Appendix "A"

Acknowledgements

***Figure #1* – Particle Erosion Test Chamber**, UDRI web site, http://www.udri.udayton.edu/

***Figure #2* – Rain Erosion Test Chamber**, UDRI web site, http://www.udri.udayton.edu/